APPENDIX H – MODELING PLAN

PHASE 1 SITE CHARACTERIZATION REPORT

Prepared for

Berry's Creek Cooperating Parties Group

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In conjunction with

Project Number CHR8261

February 26, 2010

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SECTION 1

INTRODUCTION

1.1 Introduction

The Berry's Creek Study Area (BCSA or the Site) Cooperating Potentially Responsible Party Group (Group) has entered into an Administrative Order on Consent with the U.S. Environmental Protection Agency (USEPA) Region 2 to perform a Remedial Investigation/Feasibility Study (RI/FS) pursuant to the Comprehensive Environmental Response, Compensation, and Liability Act. The scope of the RI/FS, as described in the RI/FS Work Plan (Geosyntec/Integral, 2009), calls for the preparation of a modeling plan, which is presented in this document.

The objectives of this Modeling Plan are to:

- Describe the sequential process by which models will be applied during the BCSA RI/FS to support site management decisions.
- Describe the components of the system that will be modeled (e.g., physical, chemical, and biological).
- Describe the types of data that will be collected and the types of analyses that will be conducted to support refinement of the models throughout the RI/FS process.

Models are written, schematic, and/or mathematical (analytical or numerical) descriptions of system processes that are used to organize information and illustrate key relationships (Wainwright and Mulligan, 2004). Models will be developed for the following components:

- Physical System – with a focus on hydrodynamic and sediment/particle transport modeling.
- Chemical System – with a focus on characterizing the fate, transport and bioavailability of the primary chemicals of potential concern (COPCs).
- Biological System – with a focus on understanding the biological uptake and food-web transfer of primary COPCs.

Consistent with the Contaminated Sediment Remediation Guidance for Hazardous Waste Sites (USEPA, 2005), this Modeling Plan emphasizes the development and refinement of conceptual site models (CSMs) as the foundation upon which risk is evaluated and remedial approaches are considered. As with all estuarine environments, the physical template is the base of the CSM upon which the chemical and biological elements are structured. As such, it is important that modeling be conducted within the context of both the BCSA watershed and how the BCSA interacts with the larger Hackensack River watershed. The watershed-scale approach implemented for the BCSA RI/FS recognizes this importance and is consistent with the *Contaminated Sediment Remediation Guidance for Hazardous Waste Sites* (USEPA, 2005). The following summarizes key factors related to the BCSA physical template that must be considered in model development for the BCSA:

- The BCSA is a side embayment of the lower Hackensack River estuary, and consists of tidal waterways/tributaries, large *Phragmites* marsh regions, and freshwater tributaries and wetlands. The BCSA watershed covers a total area of 31 km^2, and is a small portion of the overall 510 km^2 Hackensack River watershed.

- The construction of Oradell Dam in the 1920s substantially altered the hydrodynamic system and ecosystem of the lower Hackensack River and the BCSA. Freshwater flow into the estuary has been almost completely eliminated, resulting in a substantial landward advance of saline water, establishment of tidal advection as the dominant transport mechanism for water and sediment in the lower Hackensack River and the BCSA, creation of an environment conducive to the spread of *Phragmites*, and dramatic alteration of ecological habitats.

- The BCSA is heavily urbanized and extensive development has resulted in a considerable reduction in freshwater and tidal marsh area.

- Although small relative to tidal flows, freshwater input to the BCSA results in a moderate horizontal salinity gradient from the head of the system to the lower Hackensack River. These conditions create ecological conditions ranging from brackish to freshwater habitats.

- Unlike typical navigable channels, the BCSA is characterized by shallow waterways that are often bounded by large, shallow tidal marshes areas. These physical conditions establish a relatively low-energy environment that favors the deposition of sediments throughout the majority of the BCSA, with tidal advection from the lower Hackensack River representing the primary source of suspended sediments.

Fundamental to the evaluation of risk and remedy at the Site is developing an understanding of: 1) the key physical, chemical, and biological processes within compartments of the BCSA (e.g., reaches, marshes), 2) how these processes relate to one another, and 3) the exchange between each of the compartments and with the lower Hackensack River. Models can be powerful tools to describe these processes, relationships, and exchanges in a qualitative and/or quantitative fashion and to forecast the effects of changing conditions (e.g., in response to remedial action).

The Modeling Plan is organized into the following sections: 1) Introduction, 2) Overview of the Modeling Plan, and 3) Scope of the Phase 2 Modeling-Related Work. The Modeling Plan describes a sequential process by which models will be applied during the BCSA RI/FS to support site management decisions. An emphasis is placed on the collection of a robust empirical data set to support the development of accurate and comprehensive CSMs. These CSMs will serve as the foundation for site risk management and remedy decisions, and will be supported by empirical, analytical and/or numerical modeling, as needed, to address specific study questions.

SECTION 2

OVERVIEW OF THE MODELING PLAN

2.1 Overview

This section summarizes the progressive sequence of modeling planned for the BCSA during the RI/FS process. Emphasis is placed on the development of a robust empirical data set and CSMs characterizing the key processes influencing current and future risk at the Site. A step-wise progression to more complex modeling will be made based on an evaluation of what risk assessment or remedial alternative analysis questions cannot be answered by empirical (i.e., statistical) and analytical calculations, and therefore might be better understood using more complex numerical models. The importance of utilizing this approach is underscored in the Contaminated Sediment Remediation Guidance for Hazardous Waste Sites (USEPA, 2005).

The Modeling Plan for the BCSA is summarized with the following sequence of steps that track the phases of the RI/FS:

1. **RI/FS Work Plan**. The pre-RI data (scoping studies and other relevant studies) and knowledge of estuarine systems were used to develop a set of CSMs (physical, chemical and biological) that were presented in the RI/FS Work Plan.

2. **Phase 1 Field Work**. The Phase 1 field work began the process of qualitatively and quantitatively describing components of the CSMs, their relationships and exchanges between the physical, chemical, and biological components of the BCSA ecosystem.

3. **Phase 1 Data Analysis**. Physical, chemical and biological data from the Phase 1 field work have been used to describe and quantify the observed behavior among some system components and variables, and to validate and/or refine the CSMs. The process includes preliminary interpretation of the modeling-related data findings in relation to the risk assessment, remedial alternatives and study questions, to the extent practical during preparation of the Phase 1 report. The data needs evaluation is focused on identifying the components of the CSMs that should be further qualitatively and quantitatively described to support the advancement of the risk assessment and alternatives analysis (See Section 3).

4. **Phase 2 Work Plan**. Continue development of a data-based description of the physical, chemical and biological systems (empirical modeling) through two types of data collection:

a. Data collection to support the description of how the components of the CSMs function over a wide range of environmental conditions.

b. Data collection that supports evaluation of the causal relationships between environmental factors and the bioavailability of chemicals of potential concern (COPCs), with data and some statistical analysis, related to risk assessment and alternatives analysis questions.

Some of these data collection tasks will result in mathematical functions relating components of the systems. This type of analytical modeling has high predictive power for the conditions under which the data were collected, but generalizations beyond these conditions have limited predictive power. However, the predictive power will be improved by data collection over a larger range of site conditions over time and, where needed, by additional analytical modeling or by including numerical modeling of some components. Given the unusually wet year and substantially higher than normal tides in 2009 (See Section 2.1.3 of Phase 1 report), another year of data collection is needed to characterize the typical range of physical, chemical, and biological conditions before deciding on the need for additional analytical modeling or adding numerical modeling.

5. **<u>Phase 2 Field Work</u>**. Complete the field studies scoped for Phase 2 and apply the findings to quantify key relationships, validate and refine the CSMs, and answer study questions.

6. **<u>Phase 2 Data Analysis</u>**. Physical, chemical, and biological data from the Phase 2 field work will be used to further describe and quantify the observed behavior among some system components and variables; and thereby validate and/or refine the CSMs. The process includes interpretation of the modeling-related data findings in relation to the risk assessment and remedial alternatives and study questions. Data needs evaluation will be focused on evaluating causal relationships and quantitatively describing exchanges among CSM components, to the extent practical and warranted, to support the advancement of the risk assessment and alternatives analysis. Integration of the different models will be explored.

   The Group will make a presentation to the USEPA on the modeling completed to date and recommendations for Phase 3 modeling and associated field data needs.

7. **<u>Phase 3 Work Plan</u>**. Repeat the planning process for the Phase 2 Work Plan, except that the Phase 3 scope will build upon the considerable knowledge developed during Phases 1 and 2, and is projected to be more focused on two determinations related to analytical and numerical modeling:

a. Determine if analytical or numerical modeling is needed to answer questions related to changes in the Site conditions beyond those likely to be encountered during the three years/three phases of the RI.

b. Determine analytical or numerical modeling needs to support the detailed evaluation of remedial alternatives (e.g., impacts of hydrology modifications to facilitate remedial measures, likely permit-equivalency requirements, reductions in the bioavailability of COPCs with remedial alternatives).

8. **Phase 3 Results Analysis and Evaluation of Treatability Study/Pilot Study Modeling Needs (if warranted)**. Following completion of Phase 3, the level of modeling is adjusted to inform the risk assessment and detailed remedial alternatives analysis. This analysis may find that uncertainty related to the projected bioavailability and biouptake reduction associated with different remedial alternatives can be reduced by more detailed modeling, which might be informed through data collection in association with laboratory and/or field-based treatability studies or pilot studies.

SECTION 3

SCOPE OF PHASE 2 MODELING-RELATED WORK

This section summarizes the modeling and modeling-related analyses completed to date and describes the types of data collection and analyses that will be conducted during Phase 2 to support modeling of the physical, chemical, and biological components of the BCSA, as well as to support the Feasibility Study screening and evaluation of remedial alternatives.

3.1 Physical System (Hydrodynamic and Sediment Transport Modeling)

Task 1 of the Phase 1 study was designed to address overall data needs identified in the initial CSMs related to hydrodynamics and sediment transport in the BCSA. When complete, this task will support detailed analyses of water and suspended sediment fluxes and, in turn, COPC exchange, within the system and with the lower Hackensack River. To date, approximately 50 percent of the Phase 1 data for Task 1 is available; therefore, these analyses are in the preliminary stages, with the preliminary results presented in Section 2.1 of the Phase 1 Report.

The results of the Phase 1 investigation were applied to update the water budget calculations presented in Appendix A of the RI/FS Work Plan (Geosyntec/Integral, 2009). A box model was constructed which divided the BCSA into 18 segments (see Figures A-2 and A-15 of Appendix A of the RI/FS Work Plan; Geosyntec/Integral, 2009) and the inputs to and outputs from each segment were estimated based on available data and/or analytical calculations/modeling. In this manner, the water budget supports an evaluation of water exchange between components of the BCSA (e.g., waterways, marshes, uplands) and with the lower Hackensack River. Key refinements made to the preliminary water budget to date include:

- Tidal Prism – The tidal prism volume was calculated using GIS software based on observed tidal levels during the Phase 1 monitoring and the revised site digital elevation model based on Phase 1 marsh and tributary elevation data.

- Precipitation/Storm Water Runoff – Measured precipitation at the Teterboro airport was applied to estimate the runoff inflow volumes based on analytical modeling using the program WinTR-55 (U.S. Department of Agriculture, 2004). The modeling methodology is described in Appendix A of the RI/FS Work Plan (Geosyntec/Integral, 2009).

- Groundwater Flow – A desktop study of groundwater flow to the BCSA was completed, and included an evaluation of available literature documenting hydrogeologic conditions in the BCSA and mathematical calculations of groundwater flux based on Darcy's Law. This study is presented in Appendix D of the Phase 1 Report.

- Outfall Discharges – The water budget was updated based on discharge records available for outfalls permitted in the BCSA under the New Jersey Pollutant Discharge Elimination System (NJPDES) program.

The water budget modeling is being supported by the calculation of several parameters that describe the system hydrodynamic behavior. These calculations are summarized below.

Parameter	Equation	Description
Residence Time	$\tau = \frac{P+V}{P} \times T$	The length of time that a water parcel at a location in the system will remain in the system. V is the subtidal volume, P is the tidal prism, and T is the tidal period.
Tidal Excursion	$x = \frac{2}{\pi} U_{\max} \frac{T}{2}$	The approximate distance a particle will travel along the main axis of the system from high to low water or vice-versa. U_{max} is the maximum tidal velocity.
Tidal Dispersion Coefficient	$E = \frac{U_{ave} \times L_i}{\log\left(S/S_o \right)}$	Used in estimates of mixing by tidal dispersion. U_{ave} is the average segment velocity over a tidal cycle, L_i is the segment length, and S/S_0 is the ratio of the salinity at the head and base of the segment.
Dispersive Mixing	$T_{mix} = 0.4 \times \frac{L^2}{E}$	Time for the system to be fully mixed due to tidal dispersion, where L is the length of the system.

To evaluate sediment transport and deposition in the BCSA, a preliminary historic sediment balance was calculated. This analysis is presented in Section 3.2.2 of the Phase 1 Report. The analysis suggests that more than half of the sediment estimated to have accumulated in the marshes between 1963 and 2009 is not accounted for by runoff or autochthonous production; this finding suggests that the Hackensack River is the primary source of sediment to the BCSA. Estimated sediment transport into the BCSA with tidal flows during the time period would be more than sufficient to supply the balance of sediment accumulation not accounted for by loading from runoff and production.

The above-described empirical modeling efforts confirmed several primary elements of the physical CSMs, including:

- Tidal action from the lower Hackensack River is the dominant mechanism by which water and suspended sediments are transported into, within, and out of the BCSA.

- Freshwater inputs to the BCSA are small relative to tidal flow.

- Discharge from the BCSA to the lower Hackensack River represents a de minimis contribution to the overall flow in the River (see Appendix D of the Phase 1 Report).

- The BCSA is a low-energy side embayment environment that favors sediment deposition, especially in the upper reaches and marshes where velocities are lower.

- Tidal action is the dominant mechanism for flushing of the BCSA.

- UBC has longer tidal mixing times than other segments of the BCSA.

Empirical and analytical modeling will be conducted during Phase 2 to support the analysis of hydrodynamics and sediment transport processes and, in turn, refine the CSMs. The modeling will include a refinement of the Phase 1 modeling/calculations described above based on the combined Phase 1 and Phase 2 data sets; as well as additional empirical and analytical modeling calculations. Based on the findings of the Phase 1 investigation, the following summarizes the data needs and associated data collection during Phase 2 to support the physical system model development:

- **Hydrodynamic/Water Quality Monitoring –** The Phase 1 hydrodynamic monitoring program will be extended through Phase 2 to provide a second year of measurements of the BCSA hydrodynamic and sediment dynamics such that processes and trends can be better understood and to capture a range of conditions (e.g., rainfall conditions, major storm events, tides, seasonal trends, etc). These data will be used to refine the water budget calculations described above. Specific analyses will include:

    - **Tidal Prism Calculations –** Estimates of the tidal prism, both for the BCSA in its entirety and along study segments, will be calculated as described above and refined to consider the range of tidal conditions observed over the entire monitoring record.

    - **Water Budget** – The BCSA water budget will be refined as described above based on the range of site conditions (e.g., tides, rainfall) observed over the monitoring record. In addition, direct measurements of storm flows in the East and West Risers will be compared to those estimated by the WinTR-55 model to assess the accuracy of the WinTR-55 model predictions of storm water runoff.

    - **Discharge Calculations –** The complete Phase 1 data set and the available Phase 2 data set will be applied to develop estimates of discharge at each of the hydrodynamic stations (see Section 2.1.3.1 of the Phase 1 Report). Long-term net discharge will be evaluated over the entire monitoring record, as well as for time periods corresponding to a range of site conditions (e.g., dry weather, average storm event, major storm event, neap and spring tides). These data will be compared to the water budget estimates of system flows during those periods to assess the accuracy of the model over a range of conditions. Collectively, the water budget and discharge calculations will support an understanding of water exchange along various compartments of the BCSA and between the BCSA and the lower Hackensack River.

  - **Flushing and Circulation** – The water quality monitoring at the hydrodynamic stations provides a continuous record of salinity and temperature distribution with tides, storm events, and other periodic processes. These data will be used analytically as described above to evaluate flushing and circulation of water as a result of tidal action and freshwater inputs over a range of site conditions. The long-term and spatially-robust data set will support these calculations for segments of the system and the BCSA on a whole, thus informing the exchange between segments and with the lower Hackensack River.

  - **Dye Study** – A dye study will be completed in Phase 2 to evaluate flushing and circulation in the system, and will be focused on quantification of the exchange of water in the UBC with the rest of the system and the exchange between the marshes and waterways. The direct empirical measurements of flushing and circulation will be used for validation of the empirical flushing/circulation model.

- **Sediment Transport and Deposition** – The comprehensive Phase 1 and Phase 2 Total Suspended Solids (TSS) and turbidity data sets will be used to develop empirical quantifications of sediment transport and deposition within/between reaches of the system and across the entire system. Specifically:

  - **Relationship of TSS to NTU** – The Phase 2 program includes a focused sampling effort to better characterize the nature of suspended particulates in the system (e.g. organic and inorganic fractions) and to establish the relationship of TSS to Nephelometric Turbidity Units (NTU) for the purposes of evaluating suspended sediment flux based on the long-term water quality data set. Data characterizing the nature and variability of suspended particulate matter (e.g., suspended particle size distribution, chlorophyll-*a*, colored dissolved organic matter, water levels, discharge rates) will be evaluated statistically to assess the relationship of TSS and turbidity to key factors influencing that relationship (e.g. suspended organic matter, tidal phase, seasonal trends, rainfall/runoff). These analyses will be used to support estimation of organic and inorganic sediment transport over a range of site conditions (see below).

- **Sediment Balance –** The flux of suspended sediment within segments of the BCSA and between the Hackensack River and the BCSA will be evaluated based on the combined Phase 1 and 2 data sets. The flux at each hydrodynamic station will be calculated over time based on the estimated water discharge (see above), measured turbidities, and the NTU to TSS relationships (see above). Sediment flux will be computed for each of the bins for which water flux was calculated from the transecting data (see Section 2.1.3.1 if of the Phase 1 Report) according to the following equation:

$$F = \int_0^h 1000 \cdot w \cdot u \cdot c dz$$

  Where F is sediment flux (mg/s), w is the unit width of the depth cell (m), c is sediment concentration or TSS (mg/L), u is the normal component of velocity (m/s), and h vertical length of the depth cell (m). These calculations will support an understanding of sediment exchange between various segments of the BCSA and between the Hackensack River and the BCSA, across the range of conditions observed during the Phase 1 and 2 monitoring periods. Field measurements of loading of suspended and bed sediments from upland areas, coupled with the quantification of the sediment exchange with the lower Hackensack River and estimates of autochthonous production, will provide an understanding of the sediment balance within the system and the degree of deposition.

- **Development of Organic Matter CSM** – Marshes are recognized as a dominant source of organic matter in estuaries (USFWS, 2005; Bianchi, 2007), and export both dissolved and particulate carbon to waterways (Koch and Gobler, 2009). *Phragmites* generates significant amounts of detritus on the marsh surface (Windham, 2001) and thereby contributes substantial amounts of organic material to the suspended pool. Phase 1 data suggest that the suspended sediments in the BCSA water column are comprised of organic and inorganic fractions. Organic matter cycling is also important to COPC fate and transport (refer to Section 3.2). The Phase 2 program includes characterization of sediment, organic carbon, and COPC exchange between marshes and the intertidal tributaries that serve as the primary pathways for marsh tidal flooding. These data will be used to develop a CSM of organic matter cycling in the BCSA.

- **Upland runoff** – The Phase 2 investigation includes a focused evaluation of storm water flows and associated suspended and bedload sediment loads to the BCSA, focusing on the East and West Risers.

The empirical models will support refinement of the physical CSMs, and will support identification of data and modeling needs for the Phase 3 investigation. Of the various components to be modeled during the BCSA RI/FS, numerical modeling is more likely to be applied to the physical system. The staged process presented here ensures that the results of any modeling fit into a clear framework addressing specific site management questions necessary to understand current and future risk at the Site and to make informed site management decisions. Additional tiers of modeling complexity (numerical modeling) will be added in Phase 3 only if they significantly improve the ability to answer critical site management questions.

3.2 Chemical System (COPC Fate, Transport, and Bioavailability)

The Phase 1 investigation included extensive characterization of COPC concentrations in sediment, surface water, and biota throughout the BCSA and within key system components, (waterway sediment bedforms, primary and secondary tributaries, intertidal marshes). In addition, data were collected for numerous ancillary parameters relevant to COPC fate, transport and bioavailability; including but not limited to dissolved oxygen, oxidation/reduction potential, salinity, temperature, dissolved and particulate organic matter, AVS/SEM, TSS, turbidity, and filtered/unfiltered analyses.

The results of the Phase 1 investigation provide a baseline characterization of the BCSA, and support refinement of the chemical system CSMs and evaluation of Phase 2 data needs. A preliminary evaluation of the potential relationships between COPC concentrations across media and between a given media and variable (e.g., organic carbon, TSS) was completed based on the available Phase 1 data using graphical and statistical methods. Although these analyses are in the preliminary stages, several key findings are apparent:

- COPCs partition predominantly to the particulate phase.
- Organic matter and sulfides exert a strong influence on COPC mobility.
- The marshes are a repository for COPC mass as evidenced by higher concentrations of many COPCs at depth in the sediment.
- Biota tissue COPC concentrations are consistently less than those predicted using literature-reported relationships and measured COPC concentrations in site sediments.
- Methyl mercury concentrations were elevated in the deep sediment core interval (10-15 cm) in marshes in UBC.
- Polychlorinated biphenyl (PCB) and similar COPCs mobility and bioavailability likely is limited by high organic carbon concentrations throughout the system.

The following summarizes key data needs and associated data collection efforts during Phase 2 to support the chemical system model development:

- **Establish relationship between particulates and COPC movement –** COPC fate and transport in the BCSA is closely linked to movement of suspended solids. Continuation of the surface water sampling and hydrodynamics program in Phase 2 will provide a long-term data set to quantify this relationship and the exchange of particulate-bound COPCs between components (segments, waterways, marshes, etc) of the BCSA. The surface water program includes quantification of COPC concentrations in unfiltered and filtered (<0.45 µm) samples similar to Phase 1. In a subset of surface water samples COPC concentrations will be evaluated after filtration across a range of filter sizes (e.g., <100 µm, <10 µm, <1µm) to provide a semi-quantitative understanding of the COPC distribution in various size fractions of interest for suspended particulate.

- **Inorganic and organic fractions –** As described in Section 3.1, the Phase 1 data indicate that the suspended sediments in BCSA water column are comprised of organic and inorganic fractions which probably correspond to distinct particulate size fractions. The Phase 2 hydrodynamics program will evaluate the nature and temporal variability of this relationship. The COPC filter size fractionation study described above will include quantification of organic carbon content such that the COPC concentration in the water column can be related to suspended particulate organic carbon content. In addition, the manual surface water sampling program will include continuation of the Phase 1 quantification of dissolved, particulate, and total organic carbon concentration in surface water.

- **Marsh/Waterway exchange –** The physical and chemical character of the intertidal marshes creates an environment that favors the sequestration of COPC mass. Understanding the potential for COPC exchange between the marshes and the BCSA waterways/tributaries is important to understanding risk and evaluating remedial alternatives. The Phase 2 program includes characterization of sediment, COPC, and organic carbon exchange between marshes and the intertidal tributaries that serve as the primary pathways for marsh tidal flooding. In addition, marsh sediment pore water will be characterized to evaluate COPC transport from the marshes to the waterways/tributaries via interflow.

- **COPC fate, transport, and bioavailability –** The above-described Phase 2 programs will support an understanding of COPC fate and transport within the BCSA. In addition, the Phase 2 investigation will include characterization of several key parameters to support detailed analysis of specific processes influencing COPC fate, transport, and bioavailability. These data include, but are not limited to, AVS/SEM concentrations, sediment organic carbon content, and oxidation/reduction potential in marsh sediments.

- **PCBs fate, transport, and bioavailability –** PCBs fate, transport, and bioavailability is closely tied to organic carbon cycling in the system. The Phase 2 program includes extensive characterization of organic matter in the water column and in sediments from the waterways and the marshes. The development of a CSM describing the cycling of organic matter in the BCSA (Section 3.1) will also provide an improved understanding of controls on PCBs mobility and bioavailability.

- **Mercury fate, transport, and bioavailability –** Methyl mercury concentrations were elevated in 0 to 5 cm and 10 to 15 cm intervals in the Phase 1 marsh cores, indicating a dynamic methylation/demethylation balance vertically in the marsh sediments. In addition, methyl mercury concentrations exhibit lateral variability within a given marsh and between marshes. Collection of high resolution sediment cores is proposed to quantify factors predicted to affect mercury methylation/demethylation in BCSA marshes. Ancillary parameters for analysis will include pH, sulfide, sulfate, and TOC. Data from these high resolution cores will be used to support an analysis of factors controlling mercury methylation/demethylation in BCSA marshes.

The Phase 2 investigation will include the development of a series of empirical models describing key biogeochemical processes affecting COPC fate, transport, and bioavailability; such as COPC sequestration through partitioning to organic carbon and mineral precipitation, and COPC biotransformation (e.g., mercury methylation). The goals of the empirical models will be used to better understand the processes that influence the current COPC speciation and distribution within the BCSA. In turn, this understanding will serve as a line of evidence in risk assessment and will facilitate predictions of the effect various remedial alternatives will have on COPC fate and transport. Statistical and analytical calculations will be performed to assess causal relationships and quantitatively describe exchanges among various components of the CSMs. Statistical analyses of data from a range of biogeochemical settings will be conducted to predict future fate and transport in the system under potentially changing conditions (e.g., following implementation of a remedial action), and to evaluate relationships between potential underlying master variables (e.g., pH, Eh, salinity, organic carbon) and the important resulting effects (e.g., methylation, sulfide precipitation, etc.). Where appropriate, geochemical modeling using widely-accepted software (e.g. PHREEQC [USGS, 2007]) will be applied to quantify the likely speciation and solubility controls (mineral phases) affecting metals COPCs mobility and bioavailability. This modeling will also support development of site specific Eh-pH diagrams if necessary to evaluate potential effects of remedial alternatives on COPC speciation, fate, and transport.

The empirical models will support refinement of the chemical CSMs and identification of data needs for the Phase 3 investigation. In addition, a new CSM will be developed based on the Phase 1 and 2 data and related analyses, as well as relevant literature, to describe the cycling of organic matter within the BCSA and to assess the importance of organic matter to COPC fate, transport, and bioavailability.

3.3 Biological System

Bioaccumulation of chemicals by higher trophic level organisms such a fish is a complex process that may include multiple uptake pathways and that may be mediated by both physical and biological factors affecting chemical bioavailability, uptake rate, and loss rate. Factors that may affect both the rate of bioaccumulation and the ultimate tissue concentrations that are achieved include many of the factors already mentioned above, including the presence of complexing factors in the sediment (such as TOC), chemical factors such as solubility, as well as physiological factors such as blood flow rate (which transports lipophilic chemicals from the site of uptake to the site of sequestration in the body), and ecological factors such as the structure of the food web and the length of the food chain between sediment/water and fish. Developing a useful predictive relationship between chemical concentrations in abiotic media and fish requires an approach that can take these factors into account.

Fundamental to this is first characterizing the ecological system, and the structure and key components of the food web that define how energy flows through the system. *Phragmites* marshes are largely detritus-based systems – that is, much of the carbon that flows through the food web has its origins in the macrophytes that comprise the marsh. Dead plant material is decomposed by bacteria and fungi into mineral components that feed other detritivores, such as blue crab, mud crab, shrimp, and insects, which in turn, feed predators in the system. Chemical accumulation, then, is influenced by the chemical concentrations and bioavailability in each of these compartments, the interrelationships between compartments, and for biomagnifying compounds, the length of the food chain from detritivore to top predator.

The Phase 1 work was largely designed to achieve two objectives related to gaining an understanding of chemical uptake and accumulation in the BCSA:

1. Gain an understanding of the composition and structure of the aquatic food web
2. Measure chemical residues in key "compartments" of the overall food web (i.e., sediments, water, biota)

The results of Phase 1 have demonstrated that the aquatic community of the BCSA is reflective of that of the larger Hackensack Meadowlands region, with mummichog and white perch dominating the fish community and blue crab a prominent member of the detritivore community. Top aquatic predators such as striped bass are extremely infrequent (<1% of the catch), likely due to a combination of the low dissolved oxygen conditions prevalent in the BCSA and lower Hackensack River and the size of the available habitat especially in the upper reaches of the study area (small, shallow waterways) that are not likely to support larger fish. Residue data in mummichog indicate that uptake/accumulation is occurring and that COPC residues in mummichog track with increasing concentrations in sediments and surface waters. Residue data in white perch were higher than in mummichog (possibly because white perch may be feeding at a higher trophic level than mummichog) and did not demonstrate as clear a spatial signal (possibly because this species can migrate to areas outside of the BCSA during parts of its life cycle and be exposed to COPCs outside the BCSA).

Additional information is needed to better understand both the structure and composition of the BCSA food web and the magnitude, distribution, and bioavailability of COPCs in surface waters, sediments, and detritus. Several proposed elements of the Phase 2 program will address these data needs:

- **Marsh detritus/vegetation sampling.** If the BCSA is a detritus based system as has been shown in other *Phragmites* marshes, understanding the COPC concentrations in the different vegetative compartments will be helpful for understanding the potential COPC loading from the marshes to the waterways as well as the potential exposures in detritivores that feed on the marsh surface (e.g., insects, mummichog).

- **Carbon flow and foodweb structure.** Stable isotopes ($\delta^{15}N$, $\delta^{13}C$, and $\delta^{34}S$) will be measured in the following food web components, to the extent they are abundant enough to be readily sampled and ecologically relevant in the study area to aid in an understanding of the overall structure of the food web within the BCSA and the degree to which energy flow is linked to the marshes:

  - Primary producers and detritus*:* *Phragmites* plants (living and dead), marsh surface litter, benthic microalgae, suspended organic matter/phytoplankton)

  - Aquatic invertebrates: Blue crab, mud crab, fiddler crab, amphipods, shrimp, and infaunal benthic organisms

  - Fish: mummichog and white perch.

- **Fish dietary studies.** Fish gut contents will be analyzed in the dominant and most abundant fish in the BCSA – mummichog as a 1^{o} and 2^{o} level consumer; and white perch as a 2o level consumer. The composition of the diet as well as the fraction (weight basis) that the different diet components represent will be used to understand key linkages between aquatic species in the system.

- **COPC residues.** COPC residues will again be collected in sediment, surface water, and fish and crab COPC residues in mummichog, white perch, and blue crab also will be collected from reference areas to help determine whether the COPC residues measured in these species within the BCSA is reflective of regional background or a site signature. In addition, a more targeted investigation of COPC concentrations in the shallower aerobic zone sediments to which mummichog and its prey might be exposed will be conducted in Phase 2 to potentially support a more precise understanding of correlations between COPC concentrations in sediment and mummichog. The proposed aerobic zone sediment sampling will occur in shallow, intertidal mudflats, where mummichogs are most active.

- **COPC bioavailability.** As described above, a variety of data will be collected to better characterize the abiotic factors that influence COPC bioavailablity.

Collectively, these data will be used to explore bioaccumulation and biomagnification processes in the BCSA.

There are three commonly used approaches to interpreting bioaccumulation data: 1) use of graphical and statistical models, 2) use of steady-state mechanistic models, and (3) dynamic mechanistic models. Of these two alternatives, graphical and statistical modeling is quicker to carry out and requires little or no additional information beyond actual site measurements. Even if a steady-state mechanistic model is to be applied, statistical modeling is valuable as an initial step that can identify factors or processes that are likely to control bioaccumulation.

To accommodate the potential complexity of the bioaccumulation process for fish, we propose to use a statistical method known as generalized linear modeling (GLM) for initial data exploration in Phase 2. The GLM method is a regression approach that incorporates both continuous and categorical variables[1], and both linear and non-linear relationships. For evaluation of bioaccumulation, the chemical concentration in fish tissue is expressed as a function of both the chemical concentration in sediment or surface water and other site-specific, chemical-specific, and species-specific factors that may influence bioaccumulation. The method is applied in an exploratory fashion, where multiple candidate bioaccumulation models are formulated and then evaluated. The models used may include both simple models (i.e., tissue is directly proportional to sediment) and complex models that include many factors. Models may be developed based on theoretical expectations about the bioaccumulation process, or to systematically explore a wide range of possible combinations of factors.

When multiple statistical models are applied to the same data set, some will fit the data better than others, and the ultimate goal of the analysis is to identify one (or perhaps a small number) of

[1] Continuous variables are those that are measured on a continuous scale, such as concentrations. Categorical variables are those represented by categories such as high, medium, and low, or present or absent.

models that is suitable for use in a predictive fashion. A standard model selection metric known as Akaike's Information Criterion (AIC) can be used to determine the best model(s) overall—that is, the model that best predicts chemical concentrations in fish tissue using the fewest other variables, and will be considered as part of the Phase 2 modeling effort.

Statistical models may not identify statistically significant relationships, or those relationships may have such high variability that they are not useful for making predictions. A limitation of the statistical modeling approach that may be responsible for this kind of result is that statistical models identify relationships that are (or are expected to be) present under steady-state conditions. If a comprehensive analysis of possible statistical models does not reveal any statistically significant, and usefully precise, relationship between fish tissue and sediment/surface water, this may be because either chemical concentrations in fish tissue are not controlled by concentrations in sediment/surface waters, or, alternatively that relationships between concentrations in fish tissue and sediment are not at steady state in the data used for the analysis.

At the end of Phase 2, a determination will be made on the need for additional data or other modeling approaches that can be considered in Phase 3. This could include 1) collection of additional field data under conditions that are predicted to be somewhat prevalent in the study area but not yet characterized with actual data, followed by additional statistical analysis, 2) dynamic models of non-steady-state conditions. Most commonly used bioaccumulation models (e.g., Gobas-type models) are steady-state models, and these models would not be appropriate because the results of the statistical analysis indicate that steady-state conditions do not exist and that the site data therefore cannot be used to parameterize or validate such a model.

Choosing whether, and how, to pursue further data collection or modeling requires a decision-making process that incorporates project-specific information on costs, risks, probabilities of different outcomes, and overall project timing. These factors will be considered at the end of Phase 2 and the need for or type of approach to model bioaccumulation processes to support risk analysis and remedial alternatives analysis will be evaluated.

3.4 Feasibility Study

The Phase 1 and 2 investigations are designed to establish a robust data set to support the development of accurate and comprehensive CSMs to serve as the foundation for understanding current and future risk, and to evaluate the feasibility of remedial alternatives. The data collection and empirical and analytical modeling described above will support an understanding of the critical processes influencing COPC fate, transport, and bioavailability, and how processes relate to current and future risk. By understanding these processes across a range of conditions, it will be possible to forecast the likely effects of a remedial measure on site conditions. As is discussed above, the Phase 2 program will include several empirical and analytical modeling elements to facilitate the identification, screening, and evaluation of potential remedial alternatives; and to support the identification of specific data needs to support the feasibility study in Phase 3.

SECTION 4

REFERENCES

Bianchi, T.S. 2007. *Biogeochemistry of Estuaries*. Oxford University Press, Inc. New York, NY: 706 p.

Geosyntec/Integral. 2009. Work Plan for Remedial Investigation/Feasibility Study, Berry's Creek Study Area. Prepared for Berry's Creek Cooperating PRP Group. March 12.

Koch, F., Gobler, C.J. 2009. The effects of tidal export from salt marsh ditches on estuarine water quality and plankton communities. *Estuaries and Coasts* 32: 261-275.

US Department of Agriculture, 2004. WinTR-55 Hydrologic Model. Natural Resources Conservation Service, released August 02, 2004.

USEPA. 2005. Contaminated Sediment Remediation Guidance for Hazardous Waste Sites. EPA-540-R-05-012. OSWER 9355.0-85. U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response. December.

USFWS. 2005. Planning aid report: Hackensack Meadowlands ecosystem restoration project, Bergen and Hudson counties, New Jersey. environmental contaminants issues for restoration. Prepared for U.S. Army Corps of Engineers, New York, NY. U.S. Fish and Wildlife Service, Ecological Services, Region 5, Pleasantville, NJ.

USGS, 2007. PHREEQC Interactive, version 2.14.2. A computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations. Released September 17, 2007. Available at: http://wwwbrr.cr.usgs.gov/projects/GWC_coupled/phreeqc/

Wainwright, J., and Mulligan, M. 2004. Environmental Modeling, Finding Simplicity in Complexity. John Wiley & Sons, Ltd. P. 408.

Windham, L. 2001. Comparison of Biomass Production and Decomposition between *Phragmites australis* (common reed) and *Spartina patens* (salt hay grass) in Brackish Tidal Marshes of New Jersey, USA. *Wetlands*. 21(2):179-188. (not seen, as cited in Kiviat and MacDonald 2002).